A Multi-Agent System Transient Stability Platform for Resilient Self-Healing Operation of Multiple Microgrids

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Abstract—This paper proposes a multi-agent transient stability platform for the study of self-operation of multiple microgrids. This platform combines a MATLAB-based time domain simulation of the grid’s transient stability with a JAVA-JADE (JAVA Agent DEvelopment Framework) which supports the development of multi-agent systems that utilize distributed artificial intelligence techniques that support simultaneous, geographically-distributed, and coordinated decision-making techniques. This hybrid platform leverages the numerical strengths of MATLAB with JAVA's multi-threaded decision-making capability. To that effect, the platform was tested on two complementary test cases: one to demonstrate a dynamic reconfiguration capability and another to demonstrate the decentralized dispatch of multiple microgrids. The work presents many opportunities for future developments in the domain of resilient self-healing operation of power grids.

Index Terms—Jade, microgrids, multi-agent systems, power system control, transient stability.

I. INTRODUCTION

Recently, the academic and industrial literature has coalesced around an enhanced power grid vision of the electric power grid that is intelligent, responsive, dynamic, adaptive and flexible [1]–[3]. For example, Figure 1 shows an interconnected power-grid that has been logically divided into three micro-grids which may coordinate their power flows but also mutually disconnect and operate autonomously. The “smart grid” vision has come to include a resilient, self-healing property that allows for healthy regions of the grid to continue to operate while perturbed regions bring themselves back to normal operation [4]. Such behavior has motivated the need for microgrids as semi-autonomous power grid units that can autonomously respond to grid events while coordinating their power transmission with other power grid entities. Naturally, this desired resilient self-healing behavior based upon semi-autonomous microgrids implies decentralized coordination and control schemes that correspond to each microgrid region.

The development of such schemes requires modeling and a software platform. Advanced modeling of the power grid dynamic behavior shows its response to different types of disturbances. The software platform enables the verification and validation of simultaneous, geographically-distributed, and coordinated decision-making techniques. The first has often been addressed in power system transient stability studies [5], [6] that are carried out using over-the-shelf power system software or by more formal methods from control theory [7], [8]. The second is an area of growing interest to which the multi-agent system (MAS) community has recently proposed techniques from distributed artificial intelligence (DAI) [4], [9].

To our knowledge, these two approaches have never been combined. Consequently, there exist scenarios in which the holistic behavior of a multiple-microgrid system is not fully understood [3]. For example, transient stability studies of individual microgrids may demonstrate stable behavior which may not necessarily be the case given unknown control in an adjacent microgrid [10], [11]. The recently developed multi-agent power system developments focus exclusively on the multi-agent control system algorithms rather than their impacts on the power grid behavior itself [12]. The most advanced
work has included power flow analysis physical models that
describe the grids pseudo-steady state behavior. Such analysis
does not well address the effects of dynamic reconfigurations
or uncoordinated dispatching decisions and can lead to system
instabilities [13].

This paper specifically seeks to address these needs by de-
veloping a multi-agent transient stability platform for the study
of self-healing operation of multiple microgrids. It proceeds
as follows. Section II further discusses the implications of the
gaps in the current literature on multi-agent microgrid systems.
Section III then contributes the proposed multi-agent transient
stability platform. Section IV then provides two case study
examples: a dynamic reconfiguration, and an uncoordinated
decentralized dispatch. The paper is brought to a close in
Section V.

II. BACKGROUND: THE COORDINATION AND CONTROL OF
MICROGRIDS

The coordination and control of microgrids is a subject
that has received much attention in the literature [14], [15].
This section highlights some of the currents gaps in regards
to coordination schemes for multi-agent microgrid systems.

A. Microgrid Modeling

Microgrids’ essential characteristic lays in their semi-
autonomous behavior. Each must behave as a single controlled
entity that reliably controls its constituent loads and micro-
sources. In the meantime, it must coordinate its net power
flow to the surrounding power system(s). Together, this semi-
autonomous behavior requires that [16], [17]:

• New microsources be added to the system without mod-
  ification of existing equipment.
• The microgrid connect and disconnect itself from the grid
  rapidly and seamlessly.
• The reactive and active power be independently con-
  trolled.
• The microgrid meets the grids dynamic load require-
  ments.

To that effect, a microgrid model must first consider the
different types of constituent physical elements. These include:
1) Dispatchable Generation
2) Variable Generation
3) Dispatchable Load
4) Variable Load
5) Energy Storage Systems
6) Power System Buses
7) Power System Lines

While a full discussion on the modeling of these physi-
cal elements is not feasible in this paper, it is essential to
parametrize each of these elements in terms of their power flow
and energy capacities, ramping capabilities, energy sources,
control points, their dynamic properties and their relative
incidence to each other in the network. The interested reader is
referred to introductory texts on power system operation and
control for further details [18].

The semi-autonomous microgrid behavior can be achieved
through a hierarchical control structure with three layers. These
include a primary and a secondary control, and a tertiary
dispatch [8], [19]. The first two are often associated with the
power system’s transient stability while the latter is associated
with inter-microgrid coordination.

B. Primary & Secondary Control for Transient Stability

The primary and secondary control layers is largely respon-
sible for the real-time transient stability of the power grid. It
has received comparatively speaking greater attention in the
literature. Primary control operates on a real-time feedback
control principle on the basis of local measurements [19].
Secondary control compensates for voltage and frequency
deviations that may exist in spite of the primary control. It
adjusts setpoints dynamically to achieve minimum and stable
deviations while the power system transitions to new operating
points [8]. This functionality is particularly important after
large disturbances such as generator or load faults. As in larger
power systems, microgrid stability issues may be classified as
small signal, transient and voltage stability [5]:

• Small signal stability in a microgrid is related to feed-
  back controller, small load change and power limit of the
  micro-sources.
• Transient stability problem in a microgrid is related with
  a fault, loss of a micro-source, islanding and large load
  change.
• Reactive power limits, load dynamics and tap changers
  create most of the voltage stability problems in a micro-

grid.

Many approaches to microgrid transient stability control
such as turbine governors and automatic voltage regulators
have been borrowed from traditional power systems [5], [20]. Microgrids, however, pose greater challenges as each
generator or load makes up a comparatively large portion
of the power flow. As a result, any individual disturbance
can have a significantly larger impact on the power system
stability. Similarly, further transient stability is required to
address disturbances originating within a microgrid that impact
neighboring microgrids under potentially different operational
jurisdiction.

C. Secondary and Tertiary Coordination by Multi-Agent Sys-
tems

Tertiary coordination refers to the power systems dispatch in
order to restore secondary control reserve, manage line conges-
tion, and bring frequency and voltage deviations back to their
targets [19]. Traditionally, tertiary coordination is posed as a
centralized optimization program such as economic dispatch
or unit commitment which is executed by an independent
system operator or power utility which has a jurisdictional
monopoly over the region’s many generation facilities. Their
direct application to microgrids is limited for two reasons,
however. First, each individual microgrid may have only a
few microsources to be dispatched; so reliability demands
often overshadow economic optimization. Second, a multiple
microgrid system may not necessarily have a centralized organization that can centrally optimize on their behalf.

In contrast, multi-agent system technology promise to address a number of specific multi-microgrid operational challenges [21]. These include:

- The micro-sources either within a microgrid or across microgrids may have different owners. Decentralized coordination facilitates each owner’s unique management interest.
- Each microgrid may operate in a liberalized market and hence should maintain a certain level of “intelligence” as it bids and participates.
- Each microgrid can operate autonomously in the absence of communication systems or cooperatively using potentially any of a number of available communication technologies.
- Each microgrid can dynamically and flexibly adapt to the activities occurring in neighboring microgrids and power systems.

Multi-agent systems achieve these needs for simultaneous, geographically distributed and coordinated decision-making with the control design of each agent. They exhibit the following characteristics [12], [21]:

- The (virtual software) agent must represent a physical entity so as to control its interactions with the rest of the environment.
- The agent must sense changes in the environment and take action accordingly.
- The agent must communicate with other agents in the power system with minimal data exchange and computational demands.
- The agent must exhibit a certain level of autonomy over the actions that it takes.
- The agent has minimally partial representation of the environment.

III. A Multi-Agent System Transient Stability Platform

The coordination and control of microgrids as semi-autonomous power units suggests a decentralized control structure which may be rigorously validated and verified while still respecting the socio-economic context in which it operates. To this effect, a multi-agent system transient stability platform is proposed. This platform uses a hybrid computational platform based upon JAVA Agent DEvelopment Framework (JAVA-JADE) and MATLAB.

Following the microgrid modeling discussion found in Section II-A, the platform consists of a physical agent that is assigned to each type of physical entity found in a power grid. Figure 2 shows a unified modeling language (UML) class diagram of these seven types of agents and their composition in a microgrid. Each agent can be implemented with increasingly complex decision-making functionality which may be entirely decentralized & autonomous. Alternatively, each agent may interact and negotiate with other agents to achieve a coordinated and semi-autonomous behavior. In such a way, each microgrid has a control-action behavior that is able to respond to disturbances in the power system. Here, the JAVA-JADE platform respects that each microgrid and potentially each microsource can be managed by entirely different organizations. Furthermore, the computational platform is multi-threaded allowing simultaneous decision-making capabilities that occur in geographically distributed locations.

Despite these multiple advantages which are applicable to the multi-microgrid tertiary coordination, the JAVA-JADE environment has not been traditionally applied to physical systems where the differential algebraic equations of motion result in complex time domain simulations. Furthermore, JAVA, as a high-level programming language, is a relatively poor choice for computational applications with sophisticated numerical methods.

As shown in Figure 2, this barrier is overcome with the choice of MATLAB as a computationally appropriate environment for the time domain simulation of the power grid transient stability and primary control. This choice brings a number of notable advantages:

- Fast Development: MATLAB comes prepackaged with numerical methods functionality including differential algebraic equation solvers and well-established toolboxes in control systems, optimization, and statistics.
- Fast Computation Time: Although MATLAB is an interpreted language, many of these prepackaged numerical methods have been previously compiled from C code.
- Flexible Development: The MATLAB language is interpreted and maintains a flexible syntax which is generally accepted to facilitate engineering application development over traditional programming environments.

It is worth noting that these advantages serve only the simulation of the physical grid and its primary and control. MATLAB is primarily a single-threaded programming language. Therefore, it can not execute two or more programs in parallel. Nor can it support peer-to-peer message transfer. As a result, it is incapable of achieving the previously mentioned multi-agent system functionality provided by the JAVA-JADE environment.

Therefore, this hybrid multi-agent system transient stability platform leverages the strengths of each computational environment and avoids their respective weaknesses. The interfacing of these two environments is achieved by an open-source JAVA application called “Matlabcontrol” which allows for calling MATLAB from JAVA while still supporting multi-threaded simulation [22]. As shown in Figure 2, “Matlabcontrol” acts as a communication middleware allowing the MAS to send and receive data to and from the multiple microgrids represented in MATLAB. In order to facilitate the coordination of this information, a single facilitator agent is implemented to route information to the appropriate computational entity.

In summary, the hybrid platform works along the following operating principle: 1.) The MAS makes decentralized but coordinated decisions. 2.) These are sent as reconfigurations and setpoint actions to the MATLAB power grid simulation environment.
through the Facilitator-Matlabcontrol interface. 3.) Matlab executes a time domain simulation of the power grid transients. 4.) the power system state variables are sent back to the MAS via the Facilitator-Matlab control interface.

IV. CASE STUDY: RESILIENT SELF-HEALING OPERATION

The MAS transient stability platform described in the previous section was developed with the intention for further investigations into resilient self-healing operation of multiple microgrids. To that effect, it was tested on two complementary test cases: one to demonstrate a dynamic reconfiguration capability and another to demonstrate the decentralized dispatch of multiple microgrids.

A. Self-Healing by Dynamic Reconfiguration

To initiate studies into resilient self-healing microgrid operation, the 6-Bus system depicted in Figure 3 was chosen from Saadat’s power systems text [18].

In this example, the microgrid operates normally for 0.1 seconds, at which point Bus 6 undergoes a three-phase fault which is ultimately cleared 0.4 seconds later by the removal of Line 5-6. A 2.0pu damping was added to three synchronous generator microsources to demonstrate the return to equilibrium. Figure 4 shows the time domain simulation of the phase angles and speeds of three synchronous generators. It demonstrates that the 0.4 fault clearing time was sufficient to restore transient stability despite large deviations in relative phase angles and speeds.

Here the two dynamic reconfigurations of “Fault Bus 6” and “Remove Line 5-6” were sent as scripted-commands initiated by the microgrid agent. The longevity of the dynamic oscillations found in the time domain simulation shows that if resilient self-healing operation were to be further investigated by multi-agent systems, it would necessarily require the power system transient stability studies for formal verification and validation. In this case, the dynamic reconfigurations were scripted commands but future work can initiate such commands from agent-based decision-making functionality.

B. Decentralized Dispatch of Multiple Microgrids

To initiate studies into decentralized decision making, the 6-Bus microgrid system depicted in Figure 3 was used as a template for a 3-microgrid power test system. The three microgrids were connected at the following bus pairs: 1.5-2.1, 1.6-3.6, 2.5-3.1 where the two digit numbering convention
denotes the microgrid number followed by the original bus number. In this example, each microgrid JADE agent initiated its own economic dispatch independently in response to 10%, 5% and 15% increases in demand in microgrids 1, 2 and 3 at T=5sec, T=10sec, and T=15sec respectively. The results of each microgrid dispatch were sent to the MATLAB environment for a time domain simulation of the full power system. As Figure 5 shows, each new microgrid dispatch setpoints ripple through the 3-microgrid system as a whole causing the need for one microgrid to be able to respond to grid conditions outside of its authority.

This 3-microgrid test case demonstrates that each microgrid can be independently dispatched via a local and decentralized control algorithm. Future work can build upon these purely autonomous decision with inter-microgrid negotiations that rely on message passing. In either case, the time domain simulations motivate the need for each microgrid’s ability to respond to disturbances originating from outside of its control area.

V. CONCLUSION

This paper has proposed a multi-agent transient stability platform for the study of self-healing operation of multiple microgrids. This platform allows the time domain simulation of the grid’s transient stability while allowing the development of distributed artificial intelligence techniques that support simultaneous, geographically-distributed and coordinated decision-making techniques. To that effect, the platform was tested on two complementary test cases: one to demonstrate a dynamic reconfiguration capability and another to demonstrate the decentralized dispatch of multiple microgrids.

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